Impact of Air-Sea Interaction Research on Larger-Scale Geophysical Flows

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LONG-TERM GOALS

The long-term goals are to contribute improvements in current physical understanding and modelling of interfacial processes fundamental to air-sea interaction fluxes, particularly those involving wave breaking and associated processes of spray and spume production. Closely allied is the complementary goal of utilizing these advances to improve the reliability of operational sea state and ocean weather forecasting models, particularly for severe sea states.

OBJECTIVES

There is a strong need for improved surface flux parameterizations in the context of *coupled* atmosphere-ocean models, in applications ranging from synoptic weather systems and meso-scale ocean eddies to ocean basin scales. While not yet abundant, convincing evidence is building for significant forecast sensitivity to air-sea interface conditions for both atmospheric and sea state variables, particularly in synoptic severe marine weather predictions. Examples are given in the recent work of Janssen (2000) and Buckley and Leslie (2000), with McWilliams and Restrepo (1999) highlighting the global impact on planetary scale ocean circulation of small-scale air-sea interaction (ASI) processes.

This project seeks to improve the accuracy of coupled severe sea state/marine weather forecasting models by filling knowledge gaps in air-sea interfacial processes, with a particular focus on refining and incorporating the role of wave breaking and sea spray. Our approach is through developing more realistic parameterizations for breaking occurrence, strength and sea spray/spume source strength functions. Following validation of these new paramterizations in our test-bed models, our goal is to implement them in a coupled COAMPS(TM)/WaveWatch III model for operational sea state forecasting.

APPROACH

This project began in FY00 with an initial study (MLB) involving interactions with researchers at key international air-sea interaction/larger-scale oceanographic/meteorological research centers. The major aim was to explore knowledge gaps and establish collaborative research on key air-sea interaction problems that impact on this area. Issues identified include: Stokes' drift wave transport, Langmuir

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14. ABSTRACT

The long-term goals are to contribute improvements in current physical understanding and modelling of interfacial processes fundamental to air-sea interaction fluxes, particularly those involving wave breaking and associated processes of spray and spume production. Closely allied is the complementary goal of utilizing these advances to improve the reliability of operational sea state and ocean weather forecasting models, particularly for severe sea states.

15. SUBJECT TERMS

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circulations, misaligned wind and wave fields, departures from Monin-Obhukov similarity structure, near-surface flow separation (especially over breaking waves), contributions to air-sea fluxes from wave-correlated winds and currents including the effects of wave breaking on near-surface flow structures and fluxes, and mesoscale inhomogeneity and non-stationarity.

Arising from this initial study, a research focus emerged that identified the strength and distribution of wave breaking events, together with its associated processes, as fundamental to an improved understanding of ASI dynamics and energetics. This led to an intensive collaboration with D. Farmer and J. Gemmrich (IOS, Canada) on an extended analysis of their existing datasets. This collaboration has determined a robust threshold behavior based on a spectral measure of wave steepness that provides a unified parameterization for storm sea wave breaking probability in frequency bands at and above the wind sea spectral peak. This result promises to be very useful for parameterizing wave breaking in spectral models and in underpinning new source term formulations for the wave energy dissipation rate and spray/spume production.

In FY01, this project transitioned to a specific project within in the CBLAST hurricane modeling effort (MLB/LL) entitled ‘Wave Breaking Influence in a Coupled Model of the Atmosphere-Ocean Wave Boundary Layers under Very High Wind Conditions’. The thrust of our effort within CBLAST is the development of new parameterizations of wave breaking physics in coupled air-sea interaction models for severe sea state conditions. Russel Morison was appointed as Senior Project Scientist (Jan. 2001).

In FY02, we have continued with our parallel effort on model development and implementation issues in COAMPS/WaveWatch III. Our approach to model development has focused on refining computations of the directional wave spectrum and its tail region so that the modelled spectral saturation levels needed for predicting spectral breaking wave properties are consistent with observed levels. These can then provide reliable calculations of the enhanced fluxes between the atmosphere and ocean associated with wave breaking events. We have also formulated and implemented model strategies for (a) extracting the relevant wave breaking parameters (b) calculation of wind stress/roughness length enhancements and updating the surface layer winds accordingly. In addition, a collaborative laboratory experiment has been scheduled early in FY03 with the aim of formulating an improved spume/spray droplet source term.

WORK COMPLETED

During FY02, the collaborative research of one of the co-PI’s (MLB) with D. Farmer and J. Gemmrich (IOS, Canada) was completed on parameterizing wave breaking probability in the wave spectrum and our paper (henceforth BGF02) has been accepted for publication in the Journal of Physical Oceanography. This work is described in our FY01 Annual Report.

The energy dissipation rate source term (S_{ds}) in spectral wind wave models is central to reliable prediction of sea state and allied quantities of interest relating to wave breaking phenomena. The results from BGF02 validate and refine the underlying settings for a new saturation-based threshold form for S_{ds} that provides greater flexibility and improved performance in fetch-limited wind wave evolution modeling (e.g. Alves and Banner, 2002, henceforth AB02) and underpins our CBLAST modelling effort. The work reported in AB02 and described in our FY01 Annual Report has been extended, as described below, to address the spectral tail region in order to provide realistic calculation of its spectral energy level and directional spreading.

During FY02, significant effort also went into developing a robust methodology for predicting the spectral density of mean breaking wave crest length/unit area. This is a primary goal in our spectral wind wave modelling effort, as this quantity is central to the prediction of breaking wave enhancements to the wind stress and future development of a spray/spume source function based on sea state rather than the wind field. Our success to date is due primarily to the groundwork on S_{ds} provided by AB02 and the structural advances in predicting wave breaking probabilities at different wave scales by BGF02. The latter reported a high correlation of breaking probability with the spectral saturation $B = k^4\Phi(\boldsymbol{k}) = (2\pi)^4 f^5 F(f)/2g^2$ for wave scales from the spectral peak frequency f_p out to $2.5f_p$, and revealed a very strong threshold behavior. After normalization to offset the growing directional spreading of the waves with f/f_p, the saturation breaking threshold was found to be nearly constant from f_p out to $2.5f_p$. The AB02 form of S_{ds} was refined to incorporate the observed breaking saturation threshold. The directional characteristics of S_{ds} were also refined to provide a better match to the wind input source function S_{in} at higher wavenumbers.

A Fortran code has been developed to allow the iterative computation of the wind stress and wave spectrum in response to changes due to breaking-induced wave drag. The approach is based on the calculation of wave breaking properties from the wave spectrum, the consequent enhanced wave drag and adjustment of the aerodynamic roughness length, z_0, in the assumed logarithmic mean velocity profile for the surface layer wind field. In turn, the wave spectrum is modified in response to the updated wind profile. This is ready for introduction into the coupled test-bed model.

Joint research on refining sea spray/spume parameterization was initiated as a result of discussions at the inaugural CBLAST PI meeting in Virginia (January 2001) with C. Fairall (NOAA, Boulder, Co) and E. Andreas (USACRREL, Hanover, NH). This resulted in the scheduling of a laboratory experiment to be conducted in January/February 03 at the University of NSW Water Research Laboratory. The collaboration is aimed at developing a refined model for spume droplet production based on sea state properties (particularly wave breaking) rather than on wind speed. An initial wave breaking/turbulent flow model of spume droplet production has been developed by C. Fairall and one of the main aims of the experiment is to refine this formulation.

An allied effort has seen the acquisition of the official release of COAMPS 3 and WaveWatch III, for atmospheric and sea state prediction. Due to differences in implementation of the Message Passing Interface (MPI) parallel protocol a substantial effort has gone into coupling of these models, which is still in progress. WaveWatch III is run routinely at UNSW, and the new implementation of COAMPS3 (official version released September 2002) will soon be realized.

RESULTS

The refined S_{ds} source term was incorporated in the spectral wave evolution equation for fetch-limited growth conditions, using the nonlinear transfer source term S_{nl} based on the Tracey-Resio exact form and wind input source term S_{in} based on a modified parameterisation by Yan (1987). This form of S_{in} embodies standard observed dependences on wind parameters near the spectral peak and tail, and also provides input to the wind for waves outrunning the wind. Initial results are shown in the various panels in Figs.1 and 2 for our computations of the spectral shape properties needed for calculating spectral wave breaking, together with the predicted spectral density of breaking crest length per unit sea surface area. Where possible, these figures include comparisons with available data. These results represent a significant advance in computational sea state prediction.

Fig. 1(a) shows, for U_{10}=10 m/s, the azimuthally-integrated spectral saturation, B, as a function of f/f_p in relation to the saturation data reported in BGF02. The computation captures the levels and overall shape of the observations, aside from a more pronounced dip just above the spectral peak. Some of this is attributable to smoothing in the observed saturation spectra. Fig. 1(b) shows the saturation spectrum normalized by the local mean spreading width, against k/k_p, in relation to the normalized breaking threshold saturation level of 0.005 observed in BGF02. This indicates the spectral regions where breaking is active and how these change with wave age. The wind speed U_{10} is 10 m/s and the inverse wave age U_{10}/C_p is 1. Fig. 1(c) shows the directional spreading at different k/k_p and verifies the expected strong bimodal signature at higher k/k_p values, in accordance with the recent observations of Hwang et al. (2000). Fig. 1(d) shows the close reproduction of the modeled mean directional spreading width as a function of k/k_p, and the Hwang et al. (2000) data for comparable conditions (U_{10}~10 m/s and U_{10}/C_p~1). Fig. 2(a) compares the computed one-dimensional transect spectrum $\psi(k_1)$ with the observations of Melville and Matusov (2002), henceforth MM02. Both spectra conform to the expected k_1^{-3} behavior, but the modeled spectral level is marginally higher, corresponding very closely to the data reported in Banner (1990). Fig. 2(b) shows, for the first time, model computations of $\Lambda(c)$, the spectral density of breaking crest length/unit area of sea surface, expressed as a function of the phase speed c for comparison with the observations of MM02 and Phillips et al. (2001), henceforth PPH01. The computed results are seen to be systematically higher than MM02, but in close agreement with the levels reported by PPH01. Further research aimed at resolving these differences is in progress.

IMPACT/APPLICATIONS

Enhanced scientific understanding of severe sea state air-sea interfacial processes, particularly wave breaking, will provide better parameterizations of these processes and closely related air-sea fluxes. These improved parameterizations will lead to increased accuracy of operational sea state and marine meteorological forecasts, especially during severe marine wind conditions.

These improvements should also benefit system performance in larger-scale modeling applications, as recently published model sensitivity studies indicate that traditional ‘small-scale’ phenomena (e.g. wind waves, Langmuir cells, atmospheric roll cells) can impact significantly on improving the quality of large-scale ocean and atmospheric predictions.

RELATED PROJECTS

The ONR project *Source Term Balance for Finite Depth Wind Waves* (Young, Banner and Donelan) includes a strong focus on wave breaking observations in constant depth, shallow water environments. The results of the present study for deep water conditions has motivated a parallel analysis for the recently gathered Lake George shallow water dataset. This was pursued in FY01 and a paper was published on dominant wave breaking probability in shallow constant depth environments [Babanin et al., 2001]. The impact of wave breaking in enhancing the wind input is being investigated as part of the data analysis, which is nearing completion.

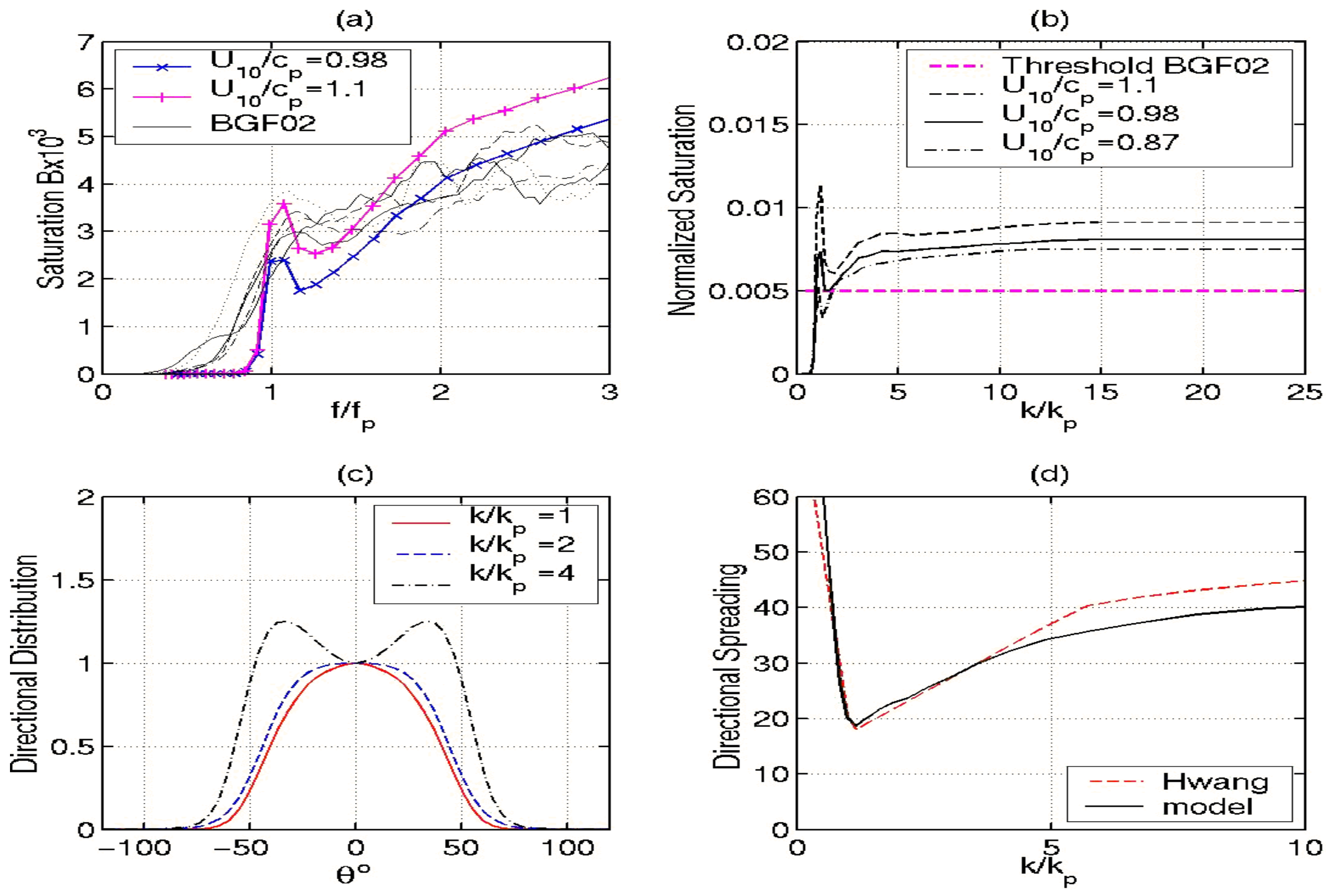

Fig. 1. (a) azimuthally-integrated spectral saturation B as a function of f/f_p for U_{10}=10 m/s, in relation to the saturation data reported in BGF02. (b) normalized saturation spectrum against k/k_p for different wave ages, with U_{10}=10 m/s. The breaking threshold saturation level of 0.005 observed in BGF02 is shown. (c) directional spreading distributions at different k/k_p for U_{10}=10 and U_{10}/C_p=1 (d) comparison of modeled mean directional spreading width versus k/k_p and the Hwang et al. (2000) data for U_{10}~10 m/s and U_{10}/C_p~1.

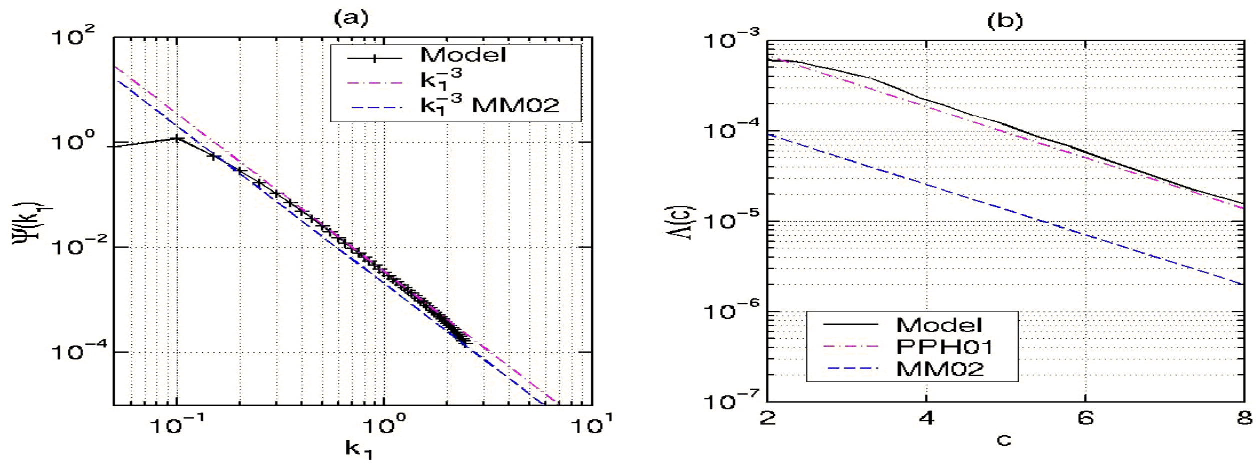

Fig. 2. (a) comparison of computed one-dimensional transect spectrum $\Psi(k_1)$ with the observations of MM02. (b) model computations of $\Lambda(c)$, the spectral density of breaking crest length/unit area of sea surface, expressed as a function of c, the phase speed. Comparison curves show observations of MM02 and PPH02. The wind speed U_{10} = 10 m/s and inverse wave age U_{10}/C_p = 0.83.

SUMMARY

This project aims to improve modeling of severe marine weather storm events, including hurricanes. It will include breaking wave effects such as sea spray and water droplets, which are believed to fuel such severe events. To date, our research has resulted in a more robust formula for wave breaking at different scales in terms of the mean steepness of the ocean waves rather than the wind speed. This ONR-sponsored research should lead to more accurate forecasts of severe storms and hurricanes over the ocean, including the likelihood of encountering dangerous large breaking waves.

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